NOAA Data Report ERL GLERL-18

HOMOGENEITY ANALYSIS OF SEASONAL MEAN TEMPERATURE SERIES AT 25 STATIONS AROUND THE GREAT LAKES

Daniel W. Gaskill

Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan
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Data available on microfiche
Contact: pubs@glerl.noaa.gov

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HOMOGENEITY ANALYSIS OF SEASONAL MEAN TEMPERATURE SERIES AT 25 STATIONS AROUND THE GREAT LAKES*

Daniel W. Gaskill

The homogeneity of seasonal mean temperature series at 25 stations around the Great Lakes is assessed. Historical documentation of inhomogeneities and graphical analysis and statistical tests for homogeneity are made for each station series in a data set available at the World Data Center-A for Glaciology. When statistical tests are significant in at least one season, the magnitude of the inhomogeneity is estimated for all four seasons.

1. INTRODUCTION

This report provides historical information on a data set, available at the World Data Center-A for Glaciology, consisting of daily maximum and minimum temperatures for 25 stations around the Great Lakes. These temperature series span the 81-year period from 1897 to 1977, inclusive. Station locations are shown in Figure 1. The historical information contained in this report documents changes in station location and instrument elevation that may have caused inhomogeneities in these temperature series. Statistical and graphical techniques described in sections 3 and 4 have been employed to estimate the magnitude of inhomogeneities found in seasonal mean temperature series derived from the daily maximum and minimum temperatures.

2. SOURCES OF INHOMOGENEITY IN CLIMATIC SERIES

The homogeneity of a climatic series refers to its representativeness over time of climatic conditions in the geographical region from which it is derived [Mitchell, 1961; World Meteorological Organization (WMO), 1966]. Each climatic record bears the imprint not only of regional climatic conditions, but of local (microclimatic) conditions as well. If a station is moved or the local environment of the recording instrument is modified in some manner, the microclimate may be affected, resulting in a discontinuity in the climatic record. In a statistical sense, changes in the local environment of the station or the instrument may result in changes in the probability distribution of the climatic element that are unrelated to fluctuations in the regional climate. It is important, therefore, that users of climatic time series be aware of inhomogeneities and adjust for them in their analyses of regional climatic fluctuations. In this report, only inhomogeneities occurring in the series of seasonal mean temperatures are analyzed.

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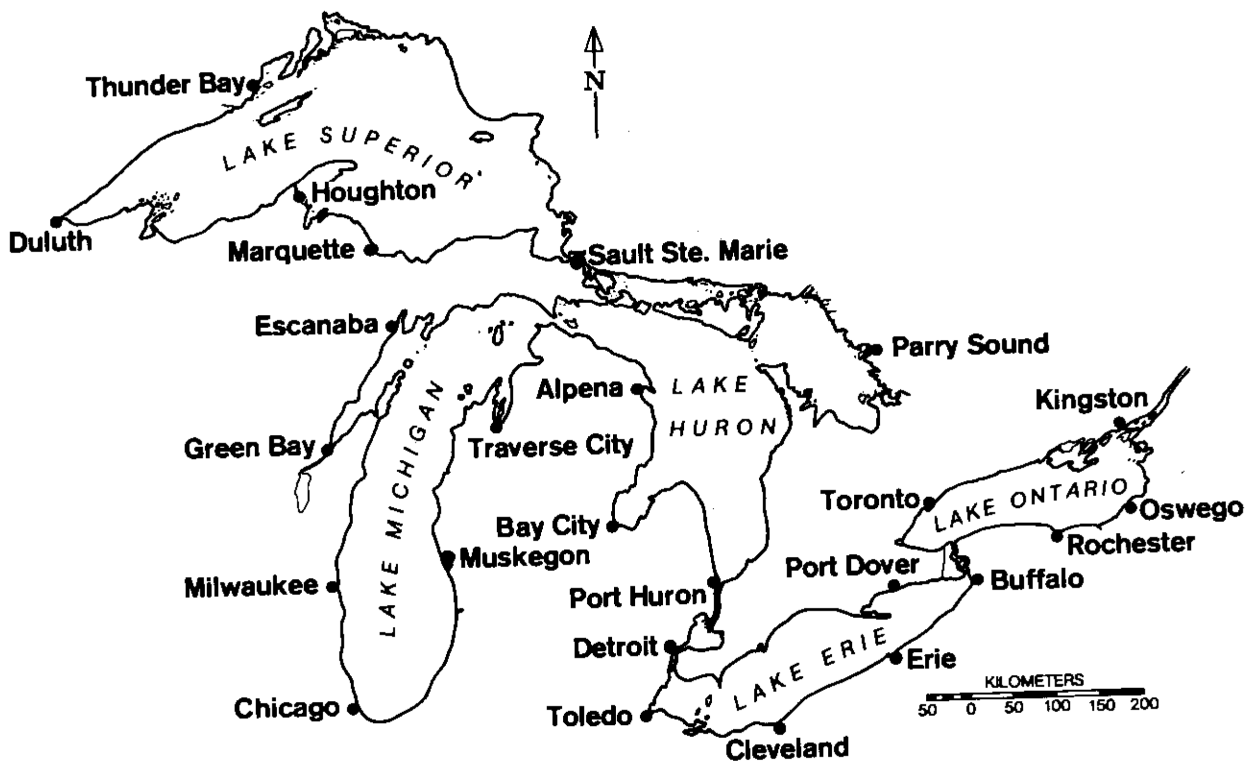

Figure 1.--*Location map of temperature stations.*

Seasons in this data report are defined by the following beginning dates: winter--December 1; spring--March 1; summer--June 1; and fall--September 1. A seasonal mean consists of a simple average of the daily mean temperatures--(max. + min.)/2--over the appropriate period.

There are three types of inhomogeneities that occur in temperature series. The first type, and the one that is often the hardest to detect and correct for, arises from a station or instrument relocation or changes in the observation program. Historical records can be quite useful in locating inhomogeneities of this type, but such documentation is not always complete or accurate. The second type involves individual seasonal means that appear to be too high or too low when compared to seasonal mean temperatures from other sites in the same climatic region. The particular cause of this kind of inhomogeneity is usually not documented, but recording errors or anomalies in the observing program are possible causes. The third type of inhomogeneity is that which accompanies a gradual change in the local environment of the sensor, such as would occur during a period of urban growth. Mitchell (1961) refers to this as a progressive inhomogeneity. The analysis presented in this report does not include progressive inhomogeneities.

3. METHODOLOGY

The first step in the homogeneity analysis of the seasonal mean temperature series for each station was to analyze historical data relating to instrument location and siting, in conjunction with graphical displays of the difference series, to locate possible discontinuities. (Graphs and historical documentation are given in appendix A). For each station, four difference series, one for each season, were computed and plotted. For each station series of seasonal means, a comparison series was first developed by averaging all other series from stations on the same lake. The difference series for each season was then computed by subtracting the "lake average" series from the series under analysis. Plots of the difference series for each season are shown in appendix A. This procedure suppresses the relatively large interannual variability that is present in these temperature series (WMO, 1966). Erroneous individual seasonal means appear as extreme outliers on these plots. Abrupt discontinuities in these series appear on the difference plots as shifts in the mean of the difference series. Care must be taken, however, in the interpretation of these plots. An extreme inhomogeneity in one series may appear as a discontinuity of smaller magnitude in the plots for other stations. Thus, in the analysis presented in this report, the difference plots have been used as a visual supplement to statistical analysis.

In order to verify the statistical significance of a suspected inhomogeneity revealed in the difference plots and/or the historical information, I used a second type of comparison series. This series consisted of a seasonal mean temperature series at a station where historical information and comparison with more than one other series of seasonal mean temperatures indicated relative homogeneity. The stations used in the comparison series and period of record used are listed in appendix B. In most cases, comparison series were used that were within 120 km of the station whose seasonal mean temperature series was being evaluated.

The basis for the comparison was, as before, a difference series computed for each season. Thus, on the basis of a homogeneous time period for both stations, the relationship between the two temperature series can be stated as follows:

$$Y_{1\tau} = Y_{2\tau} + \alpha_1 + \varepsilon_t \qquad (1)$$

or equivalently,

$$\alpha_1 = Y_{1t} - Y_{2t} + \varepsilon_t, \qquad (2)$$

where Y_{1t} is the seasonal mean temperature at time t of the series whose homogeneity is under consideration; Y_{2t} is the seasonal mean temperature at time t at the homogeneous comparison station; α_1 is the mean difference between the two series; and ε_t is an error term. Thus, if an inhomogeneity has occurred at the end of the time period used above, the relationship between the above two stations following the inhomogeneity is

$$Y_{1t} = Y_{2t} + \alpha_2 + \varepsilon_t, \qquad (3)$$

where α_2 is the new mean difference between the two series following the inhomogeneity. A statistical test for inhomogeneity that uses the null hypothesis

$$H_o: \alpha_1 - \alpha_2 = \beta = 0 \qquad (4)$$

was made for inhomogeneities suspected from historical documentation and difference plots. β is an estimate of the magnitude of an inhomogeneity resulting from a station relocation or change in observation program (i.e., the first type of inhomogeneity discussed in the previous secticn). The statistical test consisted of a two-tailed difference of means test using student's t with a pooled standard deviation. A confidence level of 0.05 was used. Values of β for specific seasons and periods are reported in section 6 for β's significantly different from zero in at least one season.

In order to evaluate individual seasonal means, I examined the plots for outliers. If individual differences in the second difference series associated with the outliers flagged on the plots were more than three standard deviations away from the mean difference, the associated seasonal mean was considered to be in error. Only homogeneous periods were used in these computations. Seasonal means considered to be erroneous are reported in section 6, along with corrected values. The corrected values were computed by adding the mean difference between the test station series and the comparison station series to the appropriate seasonal mean from the comparison station series. Thus, the estimated value would be

$$\hat{Y}_{1t} = Y_{2t} + \alpha, \tag{5}$$

where the parameter α has been estimated from the homogeneous period surrounding the seasonal mean suspected of being in error.

4. EXAMPLE CALCULATIONS AND PROCEDURES BASED ON DULUTH

4.1 Computation of Difference Series

Two difference series were computed for each station. For Duluth, the first difference series consists of the seasonal means of Duluth minus a "lake average" of seasonal means from the four other stations on Lake Superior: Thunder Bay, Houghton, Marquette, and Sault Sainte Marie. Thus, the first term of this difference series is the mean spring temperature at Duluth for the year 1897 minus the lake average spring temperature for the same year, i.e.,

$$2.6 - (1.2 + 2.3 + 2.5 + 1.6)/4 = 0.7$$

The second term is the Duluth mean summer temperature for the year 1897 minus the summer lake average temperature for the year 1897, and so on. The lake average includes all stations except Duluth. If the difference series being computed were for Thunder Bay instead of Duluth, the lake average term in the computation would include the seasonal mean from Duluth but not Thunder Bay. A plot of this difference series is shown in figure 2.

Plots of these difference series (reproduced in appendix A) show how seasonal mean temperatures at a particular location fluctuate relative to other stations around the lake. Abrupt shifts in the mean, as sometimes seen in the plots, indicate possible discontinuities. Outliers may indicate recording errors or anomalous conditions in the observing program.

The second difference series consists of seasonal means at Duluth minus the seasonal means from a comparison series at a nearby station, in this example, Two Harbors. The differencing procedure used is the same as in the previous differencing, except that the Two Harbors seasonal means replace the lake averages. The second difference series was used to estimate the magnitude of inhomogeneities identified in the documented station histories and plots of the difference series based on the lake averages. The plot of the Duluth minus Two Harbors difference series is shown in figure 3.

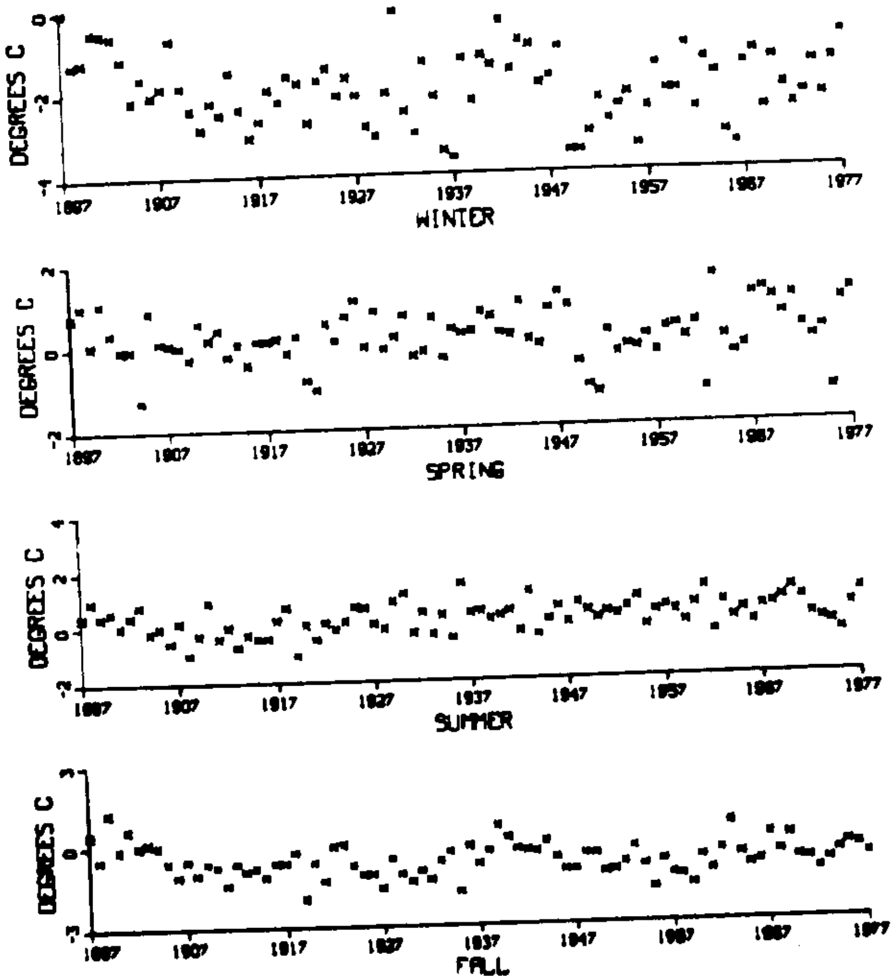

Figure 2.--*Duluth - lake average difference series, 1897-1977.*

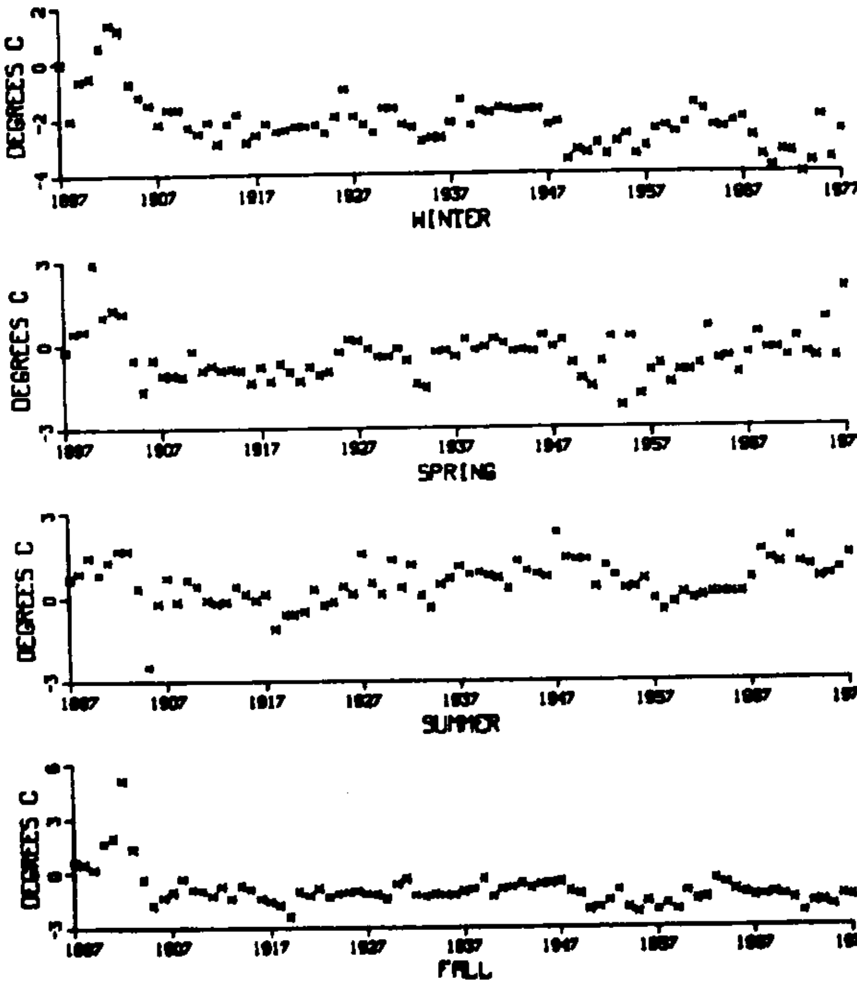

Figure 3.--*Duluth - Two Harbors difference series, 1897-1977.*

4.2 Estimation of β, Magnitude of Relative Inhomogeneity

The assumption was made that the period of record between documented inhomogeneities at a given station was homogeneous. In five instances (Marquette, Erie, Port Dover, Toronto, Chicago) this assumption proved false, as examination of the difference series in each of these cases revealed. As an example of a cause of an undocumented inhomogeneity, a meteorologist in the National Weather Service at Marquette suggested that insulation added to the roof on which the sensor was located greatly increased the amount of snow present on it in winter, thereby lowering recorded temperatures.

The procedure for estimating β involved dividing the second difference series into periods assumed to be homogeneous, based on the station history. Three such periods were identified in Duluth's record: 1897-1903, 1905-45, 1951-77. The year in which the documented change occurred was typically excluded from the estimation procedure. It should be noted that a documented change did occur in 1975, but this amounted to a reduction in elevation of the sensor by 0.31 m and was not considered significant. The longest homogeneous period in the record was chosen as a base period against which the other periods were tested.

Next, each period was examined for outliers, or extreme values, by looking at both difference series. The criterion for rejecting an extreme value for use in estimating α was that it be at least 1.4° C away from the mean difference for the period and season. (A temperature difference of 1.4° C would typically be on the order of three standard deviations from the mean in these difference series.)

The parameter α represents the mean difference for a given season in a homogeneous period. All estimates of α are based on the second difference series. The computation is a simple averaging

$$\hat{\alpha} = \frac{1}{N} \Sigma \, (Y_{1t} - Y_{2t}),$$

where N is the number of years used in the homogeneous period and Y_{1t} and Y_{2t} are defined as before. Thus, for each homogeneous period, four different estimates of α were computed, one for each season. The parameter β represents the difference between $\hat{\alpha}$ for a given season and period and $\hat{\alpha}_b$ for the same season in the base period:

$$\hat{\beta} = \hat{\alpha}_b - \hat{\alpha}.$$

A two-tailed student's t test was used to test for the statistical significance of $\hat{\beta}$. The null hypothesis is $\beta = \alpha_b - \alpha = 0$, and the test statistic is

$$t = \frac{\hat{\alpha}_b - \hat{\alpha}}{S_p\sqrt{\frac{1}{n_b} + \frac{1}{n}}} .$$

S_p is the pooled standard deviation, b is the number of years used to estimate α_b, and n is the number of years used to estimate α. The pooled standard deviation was computed with the formula

$$S_b^2 = \frac{(n_b - 1)\ S_b^2 + (n - 1)\ S^2}{n_b + n - 2} ,$$

where S_b^2 is the variance of differences for a given season in the base period and S^2 is the variance of differences for the period under test. Estimates of α and s and example computations of $\hat{\beta}$ and t are presented in table 1.

Table 1.--α, *S, and n based on Duluth - Two Harbors difference series*

Period		*Season* *Winter*	*Summer*	*Spring*	*Fall*
1897-	$\hat{\alpha}$	0.97	0.87	1.22	1.09
	S	0.44	0.38	0.41	0.64
	n	6.0	5.0	7.0	6.0
1905-49	$\hat{\alpha}_b$	-2.11	-0.6	0.41	-1.17
	S_b	0.44	0.53	0.68	0.36
	n_b	44.0	45.0	44.0	41.0
1951-77	$\hat{\alpha}$	-2.72	-0.54	0.53	-1.53
	S	0.58	0.67	0.57	0.11
	n	24.0	26.0	26.0	27.0

β's for winter 1897-1903 and test statistic were calculated as follows:

$$\beta = -2.11 - 0.97 = -3.08$$

$$t = \frac{-3.08}{0.44\sqrt{\frac{1}{44} + \frac{1}{6}}} = -15.4$$

At a significance level of 0.05, the critical value is 2.01 with 48 degrees of freedom. Since the computed t exceeds the critical value, the inhomogeneity is statistically significant in the winter season.

4.3 Examination of Individual Seasonal Means

Occasional values in these difference series appear quite extreme and justify closer examination. One way of identifying extreme values is by looking at the plots of the difference series. Extreme values appear as "spikes" or "dips" in the scatter of points.

Extreme members of the difference series were considered to indicate erroneous seasonal means when corresponding values in both difference series were extreme and when a t-test showed the individual difference in the second series was significant at the 0.001 level. This conservative test is based on considerations established for *a posteriori* significance testing. (See Brooks and Carruthers, 1953.) When the result was significant, the particular seasonal mean from the test series was corrected by substituting the corresponding seasonal mean from the comparison series corrected by $\hat{\alpha}$, computed for the particular homogeneous period. Thus, the adjusted mean value is edited for the homogeneous period of which it is a member and not the entire period of record.

Example calculations: Duluth, fall 1919.

$$t = \frac{x_i - \hat{\alpha}}{S} = \frac{-2.4 - (-1.13)}{0.36} = -3.53$$

At a significance level of 0.001 with 40 degrees of freedom, the critical value of 3.307 is exceeded. The Duluth, fall 1919, mean is edited by adding the fall $\hat{\alpha}$ for 1905-49 to the Two Harbors, fall 1919, mean,

$$6.27 + (-1.17) = 5.1.$$

5. SUMMARY

As part of a homogeneity analysis of 25 stations around the Great Lakes to determine the impact on seasonal mean temperatures of historically documented inhomogeneities, graphical analysis and statistical tests demonstrated important inhomogeneities in each station. It is important that these be adjusted for in climatological analysis using these temperature series.

6. ACKNOWLEDGMENTS

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